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Integration of CuO thin films and dye-sensitized solar cells for thermoelectric generators

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ABSTRACT

This study investigates a solar-thermoelectric module for power generation from solar energy. The proposed method uses recycled external exhaust heat to generate electric power, further enhancing the thermoelectric conversion efficiency of the thermoelectric generator (TEG). Using electrophoresis deposition, self-prepared CuO nanofluid is deposited onto a Cu plate and then adheres to the surface of a thermoelectric generator (TEG). Experimental results show that the CuO thin film coating on the TEG surface can elevate the temperature by around 2 °C and the voltage by around 14.8%, thus enhancing the thermoelectric conversion efficiency of the thermoelectric generator by 10% and increasing the overall power output by 2.35%. It was found that this solar-thermoelectric module can generate about 4.95 mW/cm^2 under solar radiation intensity of about 100 mW/cm^2.

1. Introduction

The increased worldwide demand for energy reveals the need to find new energy resources and different methods of power generation. The development of alternative energy is an imperative issue. Such energy sources include solar energy, nuclear energy, wind energy and thermal energy. Thermoelectric materials enable the conversion of electric energy to thermal energy [1]. Over the past two decades, thermoelectric devices have been widely investigated, showing that they are reliable energy converters that produce no noise or vibration due to the absence of mechanical moving parts. However, the use of TE (thermoelectric) devices is limited by their low levels of efficiency. The efficiency of a TE device is determined by its materials; therefore, this study focuses on finding better materials. Because the recycling of exhaust heat does not consider the heat input, thermoelectric materials have been applied extensively to the recycling of thermal energy [2–5]. Results obtained by Lee, Choi and Eastman in 1999 showed that a nanofluid increases the heat transfer performance far more than a suspension fluid does when added to coarse crystalline materials [6]. In 2001, Eastman et al. used a 0.3% volume ratio of nanofluid made from CuO particles 10 nm in diameter, which increased the heat transfer performance by approximately 40% over that in prior experiments [7]. In 2008, Keblinski used 6 different nanofluids to increase the heat transfer performance and concluded that nano-CuO can enhance the heat transfer performance the most effectively [8]. In 2003, Dai, Wan and Ni designed a solar-thermoelectric cooler that uses solar energy to drive a thermoelectric cooler to maintain a temperature of 5–10 °C at a coefficient of performance (COP) of 0.3 [9–11].

This study combines the advantages of DSSCs and TEG to develop a solar-thermoelectric module to generate electric power. This study assembles a thermoelectric generator (TEG) using a film structure consisting of CuO nanoparticles. The different thicknesses of the coated thin films are 0 μm, 7.36 μm, 11.73 μm, and 23.35 μm. We also compare the differences in the temperature, output power and conversion efficiency of the TEG.

2. Experimental procedure

The experimental procedures of this study can be divided into two parts. The first part involves the preparation of CuO nanoparticles by a nanofluid synthesis system [12–15]. A CuO nanoparticle suspension is used as the fabrication fluid for the electrophoresis deposition (EPD) process, with isopropanol as the dielectric fluid. Copper plate with a thickness of 0.04 mm and an

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area of 9 mm^2 is used as both anode and cathode. The distance between these two electrodes is set at 10 mm. Parallel copper plates are immersed in the CuO nanofluid, and an electric field of 50 V is applied, causing the CuO nanoparticles inside the fluid to accumulate on the surface of the copper cathode. Therefore, this study employs CuO nanopartic to prepare the thin film. The experimental devices are mainly comprised of an electrical power utility, a servo-positioning system, a vacuum chamber, a vacuum pump, a heating source, a cooling system, and a pressure control unit. The second part of the design module in Fig. 1 shows a prototype of a solar-thermoelectric module, which is composed mainly of dye-sensitized solar cells, a thermoelectric generator and CuO thin film. Parts 2–8 represent the structure of the DSSCs and part 10 is the nano-CuO heat transfer thin film which covers the cold side and hot side of the TEG by pressure. This aims to transfer the heat generated by the module rapidly to increase the thermal link of TEG instead of the electric connection. Parts 11–15 represent the interior structure of the module and the heat sink. Parts 16–18 are the exterior structure of the module.

When exposed to daylight, dye-sensitized solar cells turn solar energy into electric power. A thermoelectric generator with the hot side attached directly to the solar cells acts as an absorber, and a heat sink is directly attached to the cold side of the generator. A CuO thin film (30*30 mm^2) is attached between the DSSCs and the thermoelectric generator for heat conduction purposes. One thermoelectric cooling module (TES1-12708) was used. The heat sinks were 1 mm thick, 6 mm long in the horizontal direction and 37*37 mm^2. A CuO thin film was also attached between the thermoelectric generator and the cooling fin for heat conduction.

3. Results and discussion

Fig. 2 shows an FE-SEM image of the CuO nanoparticles produced by the proposed process. The average particle size of the CuO particles is about 80 nm long and 20 nm wide. In addition, the custom-made CuO nanofluid has better suspension while continuing to provide high thermal conductivity. The particles are evenly dispersed in 200 ml of isopropyl alcohol. As a result, a layer of the thin film structure of the CuO nanoparticles is formed, and the deposition time is set at 15 min. The thickness is 16 μm.

Fig. 3 shows the relationship between the films with different thicknesses (0 μm, 7.36 μm, 11.73 μm and 23.35 μm) with different heat source temperatures and temperature differences of the hot and cold sides. A greater and more significant temperature difference was noted after the CuO thin film had undergone electrophoresis for 24 min (23.35 μm), with the heat source temperature at 95.5 °C and the temperature difference at 11 °C. In addition, the CuO thin film coating the surface of the TEG can elevate the temperature by around 2 °C and the voltage by around 14.8%, thus enhancing the overall heat conduction and thermoelectric conversion efficiency of the thermoelectric generator by 10%.

Fig. 4 shows the relationship between the output power and the different heat source temperatures for films with different thicknesses. There was no significant difference in the thickness of the thin films when the temperature was in the range of 55–70 °C, though there was a slight difference at higher temperatures. Generally, the thickness of a thin film has little influence on the temperature difference, whereas a thermoelectric module coated by CuO thin film has better power output. In addition, a formula was used to analyze the thin film with different electrophoresis times to enhance the efficiency of the thermoelectric modules.

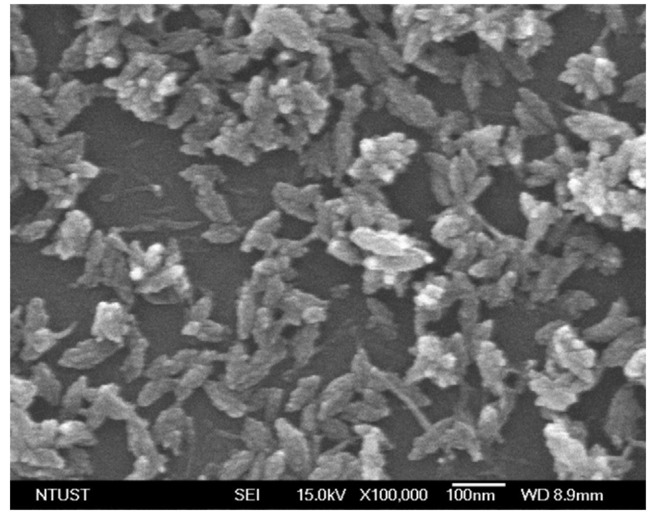

Fig. 2. FE-SEM image of the CuO nanoparticles produced by the proposed process.

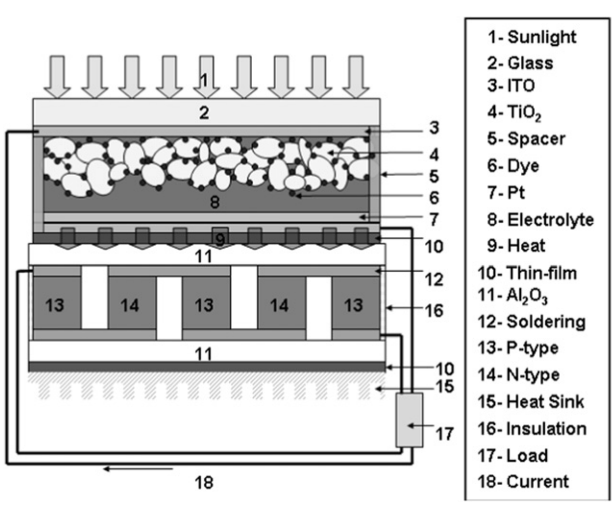

Fig. 1. Schematic diagram of a solar-thermoelectric module.

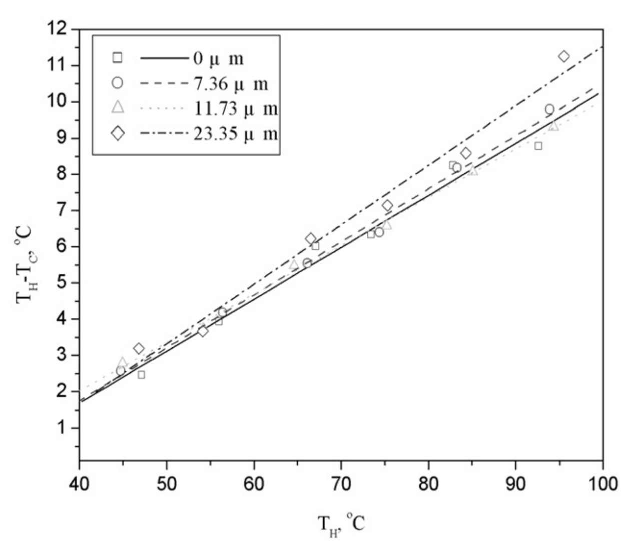

Fig. 3. Relationship between the temperature differences of the hot and cold sides of the thermoelectric chips and different heat source temperatures for thin films of different thicknesses.

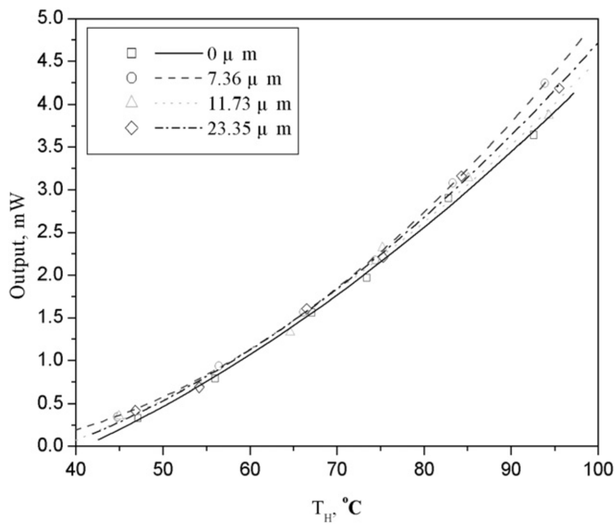

Fig. 4. Relationship between the power output of the thermoelectric chips and different heat source temperatures for thin films at different thicknesses.

Fig. 5 shows the relationship between the thermoelectric conversion efficiency and the different heat source temperatures with thin films of different thicknesses. The results show that with a hotter heat source, there is higher thermoelectric conversion efficiency. According to the results shown in Fig. 5, a thicker thin film led to better thermoelectric conversion efficiency. The CuO thin film (23.35 μm), which underwent electrophoresis for 24 min, showed the highest efficiency when the heat source temperature was 95.5 °C; its conversion efficiency was 2.12%. The conversion efficiency showed an increase of about 10%. When the recycled external exhaust heat is conducted to the CuO thin film, heat can be conducted more rapidly to the thermoelectric material through the film, producing a higher temperature gradient between the two sides of the thermoelectric material, as CuO has excellent thermal conduction. This depends on the thin film being within the range of micro-scales whose thermal conductivity diminishes as the thickness decreases. When the thin film becomes very thin, the thermal boundary resistance effects and the scattering effects of heat carriers such as electrons and phonons on the interface reduce the effective thermal conductivity of nanofilm.

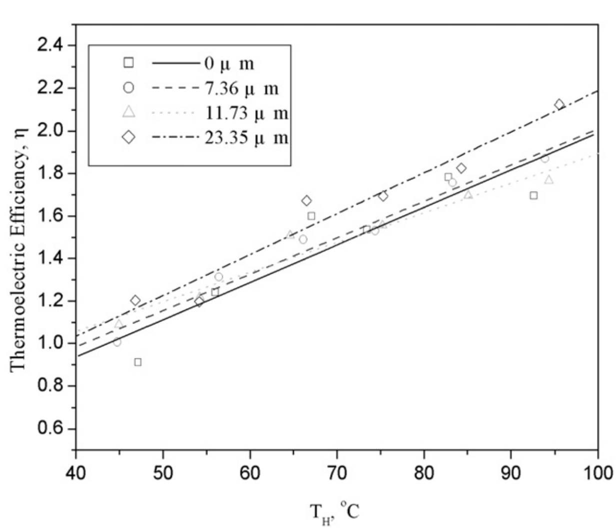

Fig. 5. Relationship between the thermoelectric efficiency as a function of TH on a Cu plate with thin films of different thicknesses.

Table 1
Photo-electrochemical parameters of the sensitized cells and TEM.

	Size (mm^3)	V_{OC} (V)	J_{SC} (mA)	FF (−)	η (%)	W (mW/cm^2)
DSSC	5*5*10	0.74	2.56	0.633	4.83	4.83
TEM	30*30*5	0.082	12.39	None	1.48	0.113

Table 1 presents the output data for the DSSCs and thermoelectric modules (TEM) under simulated solar radiation, showing that the conversion efficiency of DSSC is 4.83% and that the conversion efficiency of TEM is 1.48%. In other words, the DSSC and TEM outputs are 4.83 and 0.12 mW/cm^2, respectively. The reason for this difference is that DSSC generates electricity by light, whereas TEM generates electricity by converting heat from the substrate of the solar cell. Because the illuminated substrate of a solar cell cannot fully convert light into heat, the output of TEM is less than that of DSSC. This study analyzed the self-developed TEM and found that its power output is 4.95 mW/cm^2. Compared to the power output of pure DSSC, at 4.83 mW/cm^2, the output of TEM shows an increase of 2.35%. Furthermore, it can be acquired from the experimental data regarding the temperature variation of the hot and cold sides of a thermoelectric module under solar intensity of 100 mW/cm^2. The thickness of the prepared CuO nanofilm is 23.35 μm under the condition of electrophoresis time of 24 min. In the first 4500 s, the temperature varies. The constant part is analyzed after that time. It can be found that the surface temperature of the solar cell is about 65 °C when it is constant. The temperatures of the hot and cold sides of the thermoelectric generator are about 60.45 °C and 55 °C respectively. Moreover, when the temperatures of the hot and cold sides of the thermoelectric generator remain stable, the output current and voltage remain stable. Thus, the output current and voltage reaches a relatively constant value about 12.39 mA and 82.723 mV.

4. Conclusions

This study presents a solar-thermoelectric module concept using CuO nano thin films with DSSCs for thermoelectric power generation. The prepared module uses solar energy to generate power, and it also uses the recycled external exhaust heat to generate additional electric power which can enhances the overall output. The experimental results show that the coating of a CuO thin film onto the TEG surface can enhance the overall heat conduction and thermoelectric conversion efficiency of a thermoelectric generator by 10% and increase the overall power output by 2.35%. In addition, the prepared solar-thermoelectric module can generate about 4.95 mW/cm^2 under solar radiation intensity of about 100 mW/cm^2.

Acknowledgments

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